SPIN FORCE DEPENDENCE OF NUCLEON STRUCTURE FUNCTIONS

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Abstract

Deep inelastic structure functions for the nucleon are obtained in a constituent quark model on the light cone. In the Bjorken limit the parton model is derived. Structure functions from the hadronic tensor at the scale $\mu \sim 0.25$ GeV are evolved from $(0.6 \text{ GeV})^2$ to $-q^2 \sim 15 \text{ GeV}^2$. The model incorporates the quark boosts, is designed to describe form factors and structure functions, and to provide a link between the parton and constituent quark models. The main effect of the spin force between quarks is described in terms of smaller (and lighter) scalar $u - d$ quark pairs in the nucleon. To account for the negative slope of $F_2^n(x)/F_2^p(x)$, attraction between scalar $u - d$ quark pairs and incorporation of boosts are required. The two-body spin force between quarks from color magnetism also leads to a negative slope. The polarization asymmetry A_1^p is in fair agreement with the EMC data in the valence quark region. Revised hep-ph/9401342, Phys. Rev. D.

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I. INTRODUCTION

At low momentum transfer ($-q^2 < 0.25$ GeV^2) the nonrelativistic quark model (NQM[1]) explains many of the nucleon's static properties as originating from three valence quarks whose dynamics include a two-body confinement potential and a two-body spin force motivated by one-gluon exchange of perturbative quantum chromodynamics (QCD). The effective degrees of freedom at low energies are dressed or constituent quarks which are expected to emerge in the spontaneous chiral symmetry breakdown of QCD. Other degrees of freedom, such as gluons, are integrated out. A chiral version of the NQM may be constructed by including various soft-pion and electromagnetic amplitudes and those from quark current commutators.[2] In the NQM, estimates for the kinetic energies of the u and d quarks are of the same order as the constituent quark mass, $m_q \sim m_N/3$, leading to the conclusion that relativistic effects are important for these quarks. There are numerous contributions in the literature that include relativistic corrections to order $(v/c)^2$ in particle velocities compared to the velocity of light, or $(p/m)^2$ in momentum/mass powers. However, for a nucleon matrix element of the electromagnetic current, say, one obtains powers up to $(p/m)^{10}$. To see this, let us describe each quark by a Dirac spinor with S-wave upper and P-wave lower component in the static limit. Then the nucleon spin wave function contains products of three such quark spinors and one nucleon total-momentum spinor (see Eq. 2 below) that are coupled by Dirac matrices to the nucleon spin. Altogether the quark current contributes up to two powers of momentum and each nucleon wave function up to four giving up to ten powers for such current matrix elements. There is no a priori reason to believe that relativistic corrections of lowest order up to $(p/m)^2$ should dominate or that an expansion in p/m powers would converge rapidly.

A chief motivation for the development of the light-cone quark model is to include relativistic effects to **all** orders and avoid truncated p/m expansions. The model is formulated on the light cone for several reasons. First, in Dirac's light-cone form of relativistic quantum mechanics[3] one boost operator and two linear combinations of boost and rotation genera-

tors are kinematic, i.e.independent of interactions, which is crucial for the construction of form factors involving boosted wave functions. On the other hand, two rotation generators become interaction dependent so that rotational symmetry is more difficult to implement. Second, deep inelastic structure functions are based on the kinematics of the Bjorken limit ($q^2 \to -\infty$ and $P \cdot q \to \infty$, with the scaling variable $x = -q^2/2P \cdot q$ finite), where the virtual photon naturally probes the quark current matrix elements near the light cone.

To stay as close as possible to the NQM, the light-cone quark model uses the same parameters and nearly the same values of the NQM parameters. The constituent quark mass $m_q \sim m_N/3$, and the proton (quark core or confinement) radius is given by the inverse of the harmonic oscillator constant, $\alpha \sim m_q$, the main parameter of the confinement potential.

The light-cone quark model[4] improves the magnetic form factor fits to larger momentum transfers $-q^2 \cong 1$ to 2 GeV^2, as well as the $N \to \Delta(1232)$ $M1$-transition[5] and magnetic moments of the baryon decuplet.[6]

At high energy, though, the polarized EMC data[7] seem to imply that the quarks contribute less than 15% to the proton spin, as observed in the singlet axialvector current matrix element. This is known as the "spin crisis" caused by the EMC's polarized deep inelastic scattering (DIS) data.[8] We are using the light-cone quark model to examine this discrepancy and find that $A_1^p(x)$ can be described in the valence quark region. This result is based on several ingredients. First, the polarization asymmetry $A_1^p(x)$ and the ratio of structure functions, $F_2^n(x)/F_2^p(x)$, depend sensitively on the spin force between quarks. If there is attraction between $u - d$ quarks in the nucleon, then $A_1^p(x)$ and the negative slope of $F_2^n(x)/F_2^p(x)$ can be explained in the valence quark region, provided boosts are built into the quark model. Second, both of these DIS observables are ratios of structure functions which are only moderately affected by uncertainties inherent in a perturbative evolution from low to high momentum. Third, the vector sum of the constituent spins is not Lorentz invariant. This point has recently been emphasized by Ma et al.[9] In the rest frame of the proton the spins of the constituent quarks sum to the proton spin in the light-cone quark

model. In contrast the EMC data measure

$$\Delta q = \int dx [q^\uparrow(x) - q^\downarrow(x)],$$

where $q^\uparrow(x)$ and $q^\downarrow(x)$ are the probabilities of finding a quark (or antiquark) of flavor q with longitudinal momentum fraction x of the proton and polarization parallel and antiparallel to the proton spin **in the infinite momentum frame.** The quantity Δq is defined by the singlet axial current matrix element

$$< P, S|\bar{q}\gamma_\mu\gamma_5 q|P, S >= \Delta q S_\mu$$

in a Lorentz invariant way. Thus

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

is the sum of quark helicities in the infinite momentum frame, whereas

$$\Delta q =< M_q > \Delta q_L$$

differs from the spin sum in the proton rest frame, Δq_L, by the matrix element of an operator

$$M_q = [(p_0 + p_3 + m_q)^2 - \vec{p}_T^2]/[2(p_0 + p_3)(p_0 + m_q)]$$

that depends on the transverse motion of the quarks.

Structure functions are usually described in the parton model whose connection with the constituent quark model remains unclear. Our results provide a link beween the parton model phenomenology and light-cone quark models of the hadron spectroscopy.

The paper is organized as follows. The light-cone quark model and its nucleon wave function are introduced in Section 2. The electromagnetic form factors are presented in Section 3 and the DIS structure functions in Section 4. The light-cone form of the nucleon wave function with the spin force from color magnetism is described in Section 5. Results are discussed in Section 6.

II. LIGHT-CONE QUARK MODEL WITH SPIN FORCE

The light-cone quark model[4,5,6] is based on Dirac's light-cone form of relativistic many-body quantum mechanics,[3] where some boost generators are kinematic, i.e. interaction independent. Free Melosh rotations[10] are central in this model for the construction of non-static three-quark wave functions for the nucleon (see Eqs.1,2 below). Such a construction based on free quark spin states is also valid in models where interactions in light-cone dynamics are added to the three-quark mass (squared).[11] By comparison, bag models treat only the interacting quark relativistically and violate translation invariance.

A relativistic Gaussian wave function (see Eqs.3,7) is chosen to describe the confined quark motion while staying as close as possible to the NQM and using its parameters. More details are given in refs.4,5. To make the model more realistic, we adopt a parameterization[12] that allows us to simulate the effects of a spin force between quarks.

The need for a spin interaction in the hadronic spectroscopy is known and established.[1] Color magnetism[13] is attractive in spin 0 and repulsive in spin 1 quark pairs hence it splits the $\Delta(1232)$-nucleon, $\Sigma - \Lambda$ hyperon masses, etc. and meets the desire for a simple explanation based on quantum chromodynamics (QCD), the accepted gauge field theory of the strong interaction.

While in the nonrelativistic quark model (NQM) the strength $\alpha_s \sim 1.6$ of the OGE is unrealistically large so that its spin-orbit interaction actually spoils the success with the hadronic masses,[14] in a relativized CQM the OGE enters with a more realistic strength $\alpha_s \sim 0.6$ and its spin orbit interaction is helpful in the mass spectroscopy.[15]

The main effect of the spin interaction for the nucleon is a smaller spatial size (and lighter mass) of scalar $u - d$ quark pairs, which can be modeled by a larger transverse momentum spread $(\alpha_>)$ in the radial (relativistic harmonic oscillator) nucleon wave function ϕ_N. We adopt such a parameterization[12] in Eq.(3) for the internal proton wave function

$$\psi_N = \phi_N(13, 2)J_N(13, 2) + \phi_N(23, 1)J_N(23, 1), \tag{1}$$

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$$J_N(13,2) = \bar{u}(p_1)(\gamma \cdot P + m_N)\gamma_5 C \bar{u}^T(p_3)[\bar{u}(p_2)u_N(P)], \qquad (2)$$

$$\phi_N(13,2) \sim \exp((-1/6\alpha_>^2)[(m_q^2 + \vec{q}_{2T}^2)/x_1 + (m_q^2 + \vec{q}_{2T}^2)/x_3]$$
$$-1/(6\alpha_<^2)[(m_q^2 + \vec{Q}_{2T}^2)/x_2 + \vec{Q}_{2T}^2/(1-x_2)]), \qquad (3)$$

where

$$\alpha_<^2 = \alpha_N^2(1-D), \alpha_>^2 = \alpha_N^2(1+D)$$

and D is an adjustable deformation parameter. The light-cone spinors denoted by $u(p_i)$ or u_N are solutions of the free on-shell quark or nucleon Dirac equation with the metric conventions of ref.16; they contain the light-cone boosts. $C = i\gamma^2\gamma^0$ is the charge conjugation matrix.

The variable q_2 is the relative quark four-momentum between the up quark (#1) and down quark (#3) and Q_2 between the up quark (#2) and the ud pair (#'s1&3) so that

$$q_2 = (x_1 p_3 - x_3 p_1)/(x_1 + x_3), Q_2 = (x_1 + x_3)p_2 - x_2(p_1 + p_3) \qquad (4)$$

with $\sum_i x_i = 1$. The variables q_3, Q_3 and q_1, Q_1 are defined by cyclic permutation of the indices in Eq.4. Equivalently, the

$$\vec{Q}_{iT} = \vec{k}_{iT} = \vec{p}_{iT} - x_i \vec{P}_T$$

are the internal quark momenta with $\sum_i \vec{k}_{iT} = 0$. Transverse components (1,2) are denoted by the subscript T. The γ_5 matrix in the nonstatic spin wave function in Eq.(2) is characteristic of a quark pair (1,3) coupled to spin 0 [and similarly a quark pair (2,3) in the second term of Eq.(1)], while the $\gamma \cdot P + m_N$ originates from the Melosh transformations of free quarks to the light cone.[4,10]

III. ELECTROMAGNETIC NUCLEON FORM FACTORS

The electromagnetic form factors of the nucleon are derived from the matrix elements[4] of the J^+ current

$$< N'|J^+|N >= \int d\Gamma\{\psi_N^\dagger \sum_i \bar{u}(p_i')\gamma^+(e_i/x_i)u(p_i)\psi_N\}, \tag{5}$$

in the Drell-Yan frame, where $q^+ = 0$, so that

$$eF_1(q^2) = m_N < N(P') \uparrow |J^+|N(P) \downarrow> /P^+,$$

$$q_L eF_2(q^2)/2m_N = -m_N < N(P') \uparrow |J^+|N(P) \downarrow> /P^+, \tag{6}$$

where $\vec{q}_T = (q_1, q_2)$ and

$$q_L = q_1 - iq_2, q_R = q_1 + iq_2.$$

Substituting the nucleon wave function from Eqs.1, 2, 3 into Eq.5 we obtain

$$< N'|J^+|N >= \int d\Gamma\{2/3\phi_N(23, 1')\phi_N(23, 1)$$

$$\bar{u}'_N[p_1'](\gamma^+/x_1)[p_1]u_N Tr([P'][p_2][P][p_3])$$

$$+2/3\phi_N(1'2, 3)\phi_N(13, 2)\bar{u}'_N[p_2]u_N Tr([P'][p_1'](\gamma^+/x_1)[p_1][P][p_3])$$

$$+2/3\phi_N(23, 1')\phi_N(13, 2)\bar{u}'_N[p_1'](\gamma^+/x_1)[p_1][P][p_3][P'][p_2]u_N$$

$$+2/3\phi_N(1'3, 2)\phi_N(23, 1)\bar{u}'_N[p_2][P][p_3][P'][p_1'](\gamma^+/x_1)[p_1]u_N + (1' \leftrightarrow 2', 2 \leftrightarrow 1)$$

$$-1/3[\phi_N(23', 1)\phi_N(23, 1)\bar{u}'_N[p_1]u_N Tr([P'][p_2][P][p_3](\gamma^+/x_3)[p_3'])$$

$$+ \phi_N(23', 1)\phi_N(13, 2)\bar{u}'_N[p_1][P][p_3](\gamma^+/x_3)[p_3'][P'][p_2]u_N + (1 \leftrightarrow 2)]\}, \tag{7}$$

where the primes denote the interacting quark in the final state with momentum p_i'. We also abbreviate $\bar{u}'_N = \bar{u}_N(P')$, $u_N = u_N(P)$,

$$[p_i] = (\gamma \cdot p_i + m_q)/2m_q, [P'] = (\gamma \cdot P' + m_N)/2m_N$$

etc.

The form of the first term in Eq.7 with ϕ from Eq.3 suggests using $\vec{q}_{1T}$ and $\vec{Q}_{1T}$ as integration variables. The quark momentum variables in terms of q_1, Q_1 are given by

$$\vec{k}_{1T} = \vec{p}_{1T} - x_1 \vec{P}_T = \vec{Q}_{1T}, \vec{k}_{2T} = \vec{p}_{2T} - x_2 \vec{P}_T = \vec{q}_{1T} - x_2 \vec{Q}_{1T}/(1 - x_1),$$

$$\vec{k}_{3T} = \vec{p}_{3T} - x_3 \vec{P}_T = -\vec{q}_{1T} - x_3 \vec{Q}_{1T}/(1 - x_1). \tag{8}$$

The term with $\phi(13, 2')\phi(13, 2)$ uses $\vec{q}_{2T}$ and $\vec{Q}_{2T}$ as integration variables, while $\vec{q}_{3T}$ and $\vec{Q}_{3T}$ are used in all cross terms such as $\phi(1'2, 3)\phi(13, 2)$. Otherwise the analysis of the Dirac-spinor matrix elements and traces follows that given by our work in ref.4. The perpendicular integrals over the Gaussians are done analytically including the polynomial structure from the Dirac γ-algebra, while the remaining integrals over x_1 and x_2 are done numerically.

IV. STRUCTURE FUNCTIONS

The deep inelastic form factors $W_{1,2}$ are defined in terms of the Lorentz and gauge invariant expansion of the symmetric part of the hadronic tensor

$$W^{\mu\nu} = (-g^{\mu\nu} + q^\mu q^\nu/q^2)W_1 + W_2(P^\mu - P \cdot qq^\mu/q^2)(P^\nu - P \cdot qq^\nu/q^2)/P^2. \tag{9}$$

The hadronic tensor derives from the imaginary part of the forward virtual Compton scattering amplitude. It may be written in terms of the quark current

$$e\bar{u}(p')\gamma^\mu u(p)/\sqrt{p'^+ p^+}$$

as

$$W^{\mu\nu} = (m_q^2/m_N) \int d\Gamma \psi_N^\dagger \sum_i e_i^2/x_i \delta((p_i + q)^2 - m_q^2)\bar{u}(p_i)\gamma^\mu[p_i']\gamma^\nu u(p_i)\psi_N, \tag{10}$$

where

$$p_i' = p_i + q$$

holds for **all four** momentum components of the struck quark that becomes free in the Bjorken limit (see Eq.15 below). The imaginary part of the energy denominator (together with the denominator p'^+ of the currents) in light-cone perturbation theory supplies the $\delta((p_i+q)^2-m_q^2)$. The transverse (denoted by T) and + momentum components are conserved at the photon-quark vertex. The invariant phase space volume element

$$d\Gamma = (16\pi^3)^{-2}d^2q_i d^2Q_i dx_1 dx_2 dx_3 \delta(\sum_j x_j - 1)/x_1 x_2 x_3 \tag{11}$$

reflects the separation of the internal and c.m. motion, as the internal wave function $\psi_N(x_i, q_i, Q_i, \lambda_i)$ does not change under kinematic Lorentz transformations and translations of the nucleon. The relative momentum variables q_i and Q_i for quark i=1,2,3 are defined as in Eq.(4) for quark 2, so that

$$\vec{Q}_{iT} = \vec{k}_{iT} = \vec{p}_{iT} - x_i\vec{P}_T, \sum_i \vec{k}_{iT} = 0.$$

Substituting the wave function from Eqs.1,2 we get more explicitly for the proton

$$W^{\mu\nu} = N \int d\Gamma \{\phi_N^2(23,1)[4\bar{u}_N[p_1]\gamma^\mu[p_1']\gamma^\nu[p_1]u_N Tr([P][p_2][P][p_3])$$

$$+4\bar{u}_N[p_1]u_N Tr([P][p_2]\gamma^\mu[p_2']\gamma^\nu[p_2][P][p_3])$$

$$+\bar{u}_N[p_1]u_N Tr([P][p_2][P][p_3]\gamma^\nu[p_3']\gamma^\mu[p_3])]$$

$$+\phi_N^2(13,2)[1 \leftrightarrow 2]$$

$$+\phi_N(23,1)\phi_N(13,2)[4\bar{u}_N[p_1]\gamma^\mu[p_1']\gamma^\nu[p_1][P][p_3][P][p_2]u_N$$

$$+4\bar{u}_N[p_1][P][p_3][P][p_2]\gamma^\mu[p_2']\gamma^\nu[p_2]u_N$$

$$+\bar{u}_N[p_1][P][p_3]\gamma^\nu[p_3']\gamma^\mu[p_3][P][p_2]u_N + 1 \leftrightarrow 2]\}. \tag{12}$$

This expression may be further simplified using identities such as

$$[P][p_i][P] = \frac{1}{2}(1 + p_i \cdot P/m_q m_N)[P], \tag{13}$$

where, e.g.,

$$m_q^2 + x_i^2 m_N^2 - 2x_i p_i \cdot P = Q_i^2 = -\vec{Q}_{iT}^2 = (p_i - x_i P)^2,$$

$$m_q^2 + x_1^2 m_N^2 - 2x_1 p_1 \cdot P = [q_3 - x_1 Q_3/(1 - x_3)]^2,$$

$$m_q^2 + x_2^2 m_N^2 - 2x_2 p_2 \cdot P = [-q_3 - x_2 Q_3/(1 - x_3)]^2. \tag{13'}$$

Since

$$p_i' = p_i + q$$

holds for all four components, it is easy to verify that $W^{\mu\nu}$ of Eq.10 is gauge invariant:

$$W^{\mu\nu}q_\nu = 0 = q_\mu W^{\mu\nu}$$

involve the typical terms of the form

$$(\gamma \cdot p_i + m_q)\gamma \cdot q(\gamma \cdot p_i' + m_q) = (\gamma \cdot p_i + m_q)(\gamma \cdot p_i' - \gamma \cdot p_i)(\gamma \cdot p_i' + m_q)$$

$$= (m_q + \gamma \cdot p_i)(m_q - m_q)(m_q + \gamma \cdot p_i') = 0,$$

$$(\gamma \cdot p_i' + m_q)\gamma \cdot q(\gamma \cdot p_i + m_q) = (\gamma \cdot p_i' + m_q)(\gamma \cdot p_i' - \gamma \cdot p_i)(\gamma \cdot p_i + m_q)$$

$$= (m_q + \gamma \cdot p_i')(m_q - m_q)(m_q + \gamma \cdot p_i) = 0, \tag{14}$$

using

$$(\gamma \cdot p_i)^2 = p_i^2 = m_q^2 = (\gamma \cdot p_i')^2 = p_i'^2.$$

We define $F_1(x, q^2) = m_N W_1$ and $F_2(x, q^2) = \nu W_2$ with the energy transfer $m_N \nu = P \cdot q \to \infty$, while the longitudinal Bjorken-Feynman momentum fraction $x = -q^2/(2m_N\nu)$ stays finite in the approach to scaling as $q^2 \to -\infty$ and $\nu \to +\infty$. In the Bjorken limit

$$2P \cdot q = 2m_N\nu \to \infty, q^2 \to -\infty, 0 < x = -q^2/2P \cdot q < 1,$$

$$F_1(x, q^2) = m_N W_1(q^2, \nu) \to F_1(x), F_2(x, q^2) = \nu W_2(q^2, \nu) \to F_2(x). \tag{15}$$

In light-cone variables it is convenient to work in a frame where the nucleon moves along the z (or 3-)axis: $P^\mu = (P^+ > 0, P^- = m_N^2/P^+, \vec{P}_T = 0)$. (In the nucleon rest frame $P^+ = m_N$ and the photon energy $q_0 = \nu \to \infty$ from Eq.15.) If we take $q^z < 0$, then

$$q^- = q_0 - q^z = -2x m_N \nu / q^+ \sim 2m_N\nu/P^+ \to \infty,$$

while

$$q^+ = q_0 + q^z \sim -xP^+$$

and $\vec{q}_T$ stay finite. In fact, from Eq.15 we obtain

$$2m_N\nu(1 + xP^+/q^+) = m_N^2 q^+/P^+,$$

so that

$$q^+/P^+ = \nu/m_N\{1 - [1 + 2xm_N/\nu]^{1/2}\} = -\xi \sim -x, \tag{16}$$

as $\nu \to \infty$, where ξ is the Nachtmann variable that may also be written as

$$\xi = 2x/\{1 + [1 + 2xm_N/\nu]^{1/2}\} = -q^2/\{\nu + [\nu^2 - q^2]^{1/2}\}m_N.$$

If we use $p_i'^- = p_i^- + q^-$ for the **interacting** quark, then

$$2P \cdot q = m_N^2 q^+/P^+ + P^+\{m_q^2 + (\vec{p}_{iT} + \vec{q}_T)^2]/(x_i P^+ + q^+) - (m_q^2 + \vec{p}_{iT}^2)/x_i P^+\} \sim 2m_N\nu$$

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requires that $(q^+/P^+ = -\xi \to -x_i,or)$ $x_i \to x$ in the Bjorken limit. (Note that $q^+ < 0$ is appropriate for bosons; and the virtual photon is far off its mass shell with $q^2 \sim q^+ q^- \sim -2xm_N\nu \to -\infty$.) Equivalently, the delta function in Eq.10 may be rewritten as

$$\delta((p_i + q)^2 - m_q^2) = \delta(q^2 + 2p_i \cdot q) = \delta(q^-(q^+ + p_i^+) + p_i^- q^+ - 2\vec{p}_{iT} \cdot \vec{q}_T - \vec{q}_T^2)$$

$$= \delta(P^+ q^-(x_i - \xi) - p_i^- \xi P^+ - 2\vec{p}_{iT} \cdot \vec{q}_T - \vec{q}_T^2) \to -\xi\delta(x_i - \xi)/q^2 \qquad (17)$$

in the Bjorken limit, where also $\xi \to x$.

We are now ready to project

$$W_1 = P_{\mu\nu}^1 W^{\mu\nu}, W_2 = P_{\mu\nu}^2 W^{\mu\nu}, \qquad (18)$$

from $W^{\mu\nu}$, where

$$P_{\mu\nu}^1 = \{-g_{\mu\nu} + P_\mu P_\nu/(1 - \nu^2/q^2)m_N^2\}/2,$$

$$P_{\mu\nu}^2 = \{-g_{\mu\nu} + 3P_\mu P_\nu/(1 - \nu^2/q^2)m_N^2\}/2(1 - \nu^2/q^2). \qquad (19)$$

Using

$$\gamma_\mu[p_i']\gamma^\mu = 3 - 2[p_i']$$

in Eq.12 the typical term in $W^{\mu\nu}g_{\mu\nu}$ for the proton scales as

$$[p_i][p_i'][p_i]/q^2 = (m_q^2 + p_i \cdot p_i')[p_i]/(2m_q^2 q^2) \sim -[p_i]/4m_q^2 \qquad (20)$$

including q^{-2} from the delta function in Eq.17 and using

$$p_i \cdot p_i' = m_q^2 - q^2/2 \sim m_N\nu x.$$

Replacing effectively in $W^{\mu\nu}g_{\mu\nu}$ of Eq.12 all the terms $[p_i]\gamma^\mu[p_i']\gamma_\mu[p_i]$ by $[p_i] = (\gamma \cdot p_i + m_q)/2m_q$ generates in $W_{1,2}$ the spin structure of $\psi_N^\dagger \delta(x_i - x)\psi_N$.

All terms $\sim P_\mu W^{\mu\nu} P_\nu$ in $P_{\mu\nu}^{1,2} W^{\mu\nu}$ scale to zero because of the extra $\nu \to \infty$ in the denominator of the $P_\mu P_\nu$ terms in $P_{\mu\nu}^{1,2}$. Substituting Eqs.17,20 into Eq.12, we obtain the structure function of the parton model

$$F_1(x) = \int d\Gamma \psi_N^\dagger \Sigma e_i^2 \delta(x_i - x) \psi_N / 2 = \sum_i e_i^2 q_i(x)/2, \tag{21}$$

where the quark probabilities q_i are derived from the light-cone quark model wave function ψ_N:

$$q_{\lambda_i}(x) = \sum_{\lambda_j, j \neq i} (16\pi^3)^{-2} \int [dx][d^2\mathbf{k}_{jT}] \delta(x_i - x) |\psi_N(x_j, \mathbf{k}_{jT}, \lambda_j)|^2. \tag{22}$$

For F_2 the extra factor $\nu/(1 - \nu^2/q^2) \to 2xm_N$, so that $F_2(x) = 2xF_1(x)$ is obtained. From the normalization of the nucleon wave function ψ_N we obtain the sum rule for F_2:

$$\int dx F_2(x)/x = \sum_i e_i^2. \tag{23}$$

The polarized structure functions $g_i(x, q^2)$ are defined by the antisymmetric part of the hadronic tensor

$$W_A^{\mu\nu} = \epsilon^{\mu\nu\sigma\rho} q_\sigma [S_\rho g_1(x, q^2) + [S_\rho - P_\rho q \cdot S/(m_N\nu)] g_2(x, q^2)], \tag{24}$$

with the spin vector

$$S_\rho = \bar{u}_N \gamma_\rho \gamma_5 u_N. \tag{25}$$

In order to extract g_1 and g_2, we expand the relevant terms

$$\gamma^\mu \gamma \cdot p_i' \gamma^\nu = (p_i'^\mu \gamma^\nu + p_i''^\nu \gamma^\mu - g^{\mu\nu} \gamma \cdot p_i') + i\epsilon^{\mu\nu\sigma\rho} p_{i\sigma}' \gamma_\rho \gamma_5 \tag{26}$$

in $W^{\mu\nu}$ in Eq.10. The first three symmetric terms in Eq.26 have been included in $W_S^{\mu\nu}$ in Eq.12, while the last antisymmetric term generates $W_A^{\mu\nu}$. Omitting the $i\epsilon^{\mu\nu\sigma\rho}$ factor and noticing that $p_i' = p_i + q$ provides the only q-dependence, we obtain

$$g_2(x) \equiv 0, \tag{27}$$

and

$$g_1(x, q^2) S_\rho = \nu (m_q/m_N)^2 \int d\Gamma \psi_N^\dagger \sum_i e_i^2 //\delta((p_i + q)^2 - m_q^2) \bar{u}_i \gamma_\rho \gamma_5 u_i \psi_N / x_i.$$

In the Bjorken limit Eq.17 yields for the delta function

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$$\nu\delta((p_i + q)^2 - m_q^2) \rightarrow -x\nu\delta(\xi - x_i)/q^2 \rightarrow \delta(x - x_i)/2m_N. \tag{29}$$

The q^2 factor in Eq.29 is the only q-dependence in Eq.28. Substituting Eq.29 into Eq.28 along with the nucleon wave function ψ_N from Eqs.1,2,3 we obtain

$$g_1(x)S_\rho = (1/2)(m_q/m_N)^2 \int d\Gamma\{\phi^2(23,1)[23,1]_\rho + \phi^2(13,2)[13,2]_\rho + \phi(23,1)\phi(13,2)[I]_\rho\}, \tag{30}$$

where

$$[23,1]_\rho = 4\bar{u}_N[p_1]\gamma_\rho\gamma_5[p_1]u_N Tr([P][p_2][P][p_3])$$

$$+4\bar{u}_N[p_1]u_N Tr([P][p_2]\gamma_\rho\gamma_5[p_2][P][p_3])$$

$$-\bar{u}_N[p_1]u_N Tr([P][p_2][P][p_3]\gamma_\rho\gamma_5[p_3]),$$

$$[13,2]_\rho = [23,1]_\rho(1 \leftrightarrow 2),$$

$$[I]_\rho = 4\bar{u}_N[p_1]\gamma_\rho\gamma_5[p_1][P][p_3][P][p_2]u_N$$

$$+4\bar{u}_N[p_1][P][p_3][P][p_2]\gamma_\rho\gamma_5[p_2]u_N$$

$$- \bar{u}_N[p_1][P][p_3]\gamma_\rho\gamma_5[p_3][P][p_2]u_N + (1 \leftrightarrow 2). \tag{31}$$

We analyze Eq.31 using the identities in Eqs.13, 13$'$ and

$$[p_i]\gamma_\rho\gamma_5[p_i] = (\gamma_\rho + p_{i\rho}/m_q)\gamma_5[p_i], \tag{32}$$

$$[P][p_i]u_N = (1/2)(1 + p_i \cdot P/m_q m_N)u_N. \tag{32'}$$

This yields for the first term of $[23,1]_\rho$, for example,

$$4\bar{u}_N[p_1]\gamma_\rho\gamma_5[p_1]u_N Tr([P][p_2][P][p_3])$$

$$= 2(1 + p_2 \cdot P/m_q m_N)(1 + p_3 \cdot P/m_q m_N)\bar{u}_N(\gamma_\rho + p_{1\rho}/m_q)\gamma_5[p_1]u_N. \tag{33}$$

Integrating Eq.33 over the internal momentum coordinates yields the expression

$$(\bar{u}_N\gamma_\rho\gamma_5 u_N)\int d\Gamma\phi^2(23,1)(1 + p_2 \cdot P/m_q m_N)(1 + p_3 \cdot P/m_q m_N)e_1^2/x_1, \tag{34}$$

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which, except for the factor S_ρ, is precisely the corresponding term in the quark probability in Eq.22. The trace in the second term of $[23, 1]_\rho$,

$$4\bar{u}_N[p_1]u_N Tr([P][p_2]\gamma_\rho\gamma_5[p_2][P][p_3]) = (1 + p_3 \cdot P/m_q m_N)\bar{u}_N[p_1]u_N Tr((\gamma_\rho + p_{2\rho}/m_q)\gamma_5[p_2][P]) \quad (35)$$

vanishes obviously, and that of the third term similarly, etc. For the first term in $[I]_\rho$ we obtain

$$4\bar{u}_N[p_1]\gamma_\rho\gamma_5[p_1][P][p_3][P][p_2]u_N = (1 + p_2 \cdot P/m_q m_N)(1 + p_3 \cdot P/m_q m_N)\bar{u}_N(\gamma_\rho + p_{1\rho}/m_q)\gamma_5[p_1]u_N \quad (36)$$

which, on integrating over the internal momentum variables, yields the contribution

$$(\bar{u}_N\gamma_\rho\gamma_5 u_N) \int d\Gamma \phi(23, 1)\phi(13, 2)(1 + p_2 \cdot P/m_q m_N)(1 + p_3 \cdot P/m_q m_N)e_1^2/x_1$$

to $g_1 S_\rho$, and similar ones for all other terms in $[I]_\rho$ in Eq.31. On comparing with the individual terms in the quark probabilities in Eq.22 we find that these contributions in Eqs.34,35,36 and so on generate the longitudinal polarized structure function

$$g_1(x) = \frac{1}{2}\sum_i e_i^2[q^\uparrow(x) - q^\downarrow(x)] \quad (37)$$

of the parton model.

While the **interacting** quark is treated as a current quark in the parton model, we have obtained the same form of the structure functions using the quark currents of the constituent quark model. In ref.18 such structure function results are taken to represent the non-perturbative input at a low energy scale $\mu \sim 0.25$ GeV and are then evolved to high q^2. A perturbative QCD evolution from such a low resolution value to high q^2 is unreliable. To avoid this problem we extract the momentum dependent structure functions $F_i(x, q^2)$ from the hadronic tensor at the $\mu = 0.25$ GeV scale (before the Bjorken limit). Then we evolve them from $-q^2 = (0.6 \text{ GeV})^2$, where the relativistic quark model is clearly valid, to the $-q^2 \sim 15$ GeV^2 of the EMC data.

V. LIGHT-CONE QUARK MODEL WITH COLOR MAGNETISM

It is well known that a nucleon wave function based on the symmetric $[56, 0^+]$ representation of $SU(6)$ generates deep inelastic structure functions in disagreement with the data. In particular, the ratio of neutron-to-proton structure functions $F_2^n(x)/F_2^p(x) = 2/3$ is constant in contrast to the negative slope of the data shown in Fig.2.

In the NQM the $SU(6)$ symmetry is broken by the two-body spin interaction from color magnetism besides the constituent quark masses $m_u = m_d = m_q \neq m_s$. Its most important effect is the admixture of the $[70, 0^+]SU(6)$ configuration to the $[56, 0^+]$. In the NQM a truncated wave function may be written in coordinate space as

$$|N> = a_{56}|N, 56> + a_{70}|N, 70> \tag{38}$$

with $a_{56} = 0.95$ and $a_{70} \sim 0.2$ for $m_q = 0.33$ GeV and $\alpha = 0.32$ GeV. (Note that $a_{56} = a_S$ and $a_{70} = -a_{S_M}$ in refs.17, 18 and $|N, 70> \rightarrow -|^2S_M>$ in the static limit.) All other configurations have substantially smaller admixture coefficients except for the $2S = S'$ state which, if included, would renormalize the $1S$ radial wave function of the $[56, 0^+]$ and lower the $F_2^n(x)/F_2^p(x)$ slope. In order to evaluate deep inelastic structure functions for the N wave function in Eq.(38) we translate it to the light cone in momentum space. The Gaussian radial S-wave function

$$\phi_S = \exp[-\alpha^2(\vec{\rho}^2 + \vec{\lambda}^2)/2] \rightarrow \phi_0 = \exp[-\sum_{i=1}^{3} M_j/6\alpha^2], \tag{39}$$

where

$$\vec{\rho} = (\vec{r}_1 - \vec{r}_2)/\sqrt{2}, \vec{\lambda} = (\vec{r}_1 + \vec{r}_2 - 2\vec{r}_2)/\sqrt{6} \tag{40}$$

are the usual relative quark variables in coordinate space and

$$M_j = (\vec{k}_{jT}^2 + m_q^2)/x_j,$$

$$\sum_j M_j = \vec{q}_{3T}^2(1 - x_3)/x_1 x_2 + \vec{Q}_{3T}^2/x_3(1 - x_3) + \sum_j m_q^2/x_j. \tag{41}$$

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in light cone variables.

The $[70, 0^+]$ wave function of mixed symmetry involves the radial wave functions

$$\phi^\lambda = (\vec{\rho}^{\,2} - \vec{\lambda}^2)\phi_S, \phi^\rho = 2\vec{\rho} \cdot \vec{\lambda}\phi_S, \tag{42}$$

which are translated to the light cone using the Fourier transform

$$\int d^3\rho \exp(i\vec{p}_\rho \cdot \vec{\rho} - \alpha^2\vec{\rho}^{\,2}/2)\vec{\rho}^{\,2} = (2\pi/\alpha^2)^{3/2}\{3/\alpha^2 - \vec{p}_\rho^{\,2}/\alpha^4\}\exp(-\vec{p}_\rho^{\,2}/2\alpha^2) \tag{43}$$

and the corresponding ones for $\vec{\lambda}$ and its conjugate momentum variable $\vec{p}_\lambda$ and $\vec{\rho} \cdot \vec{\lambda}$. Note the important relative minus sign in the Fourier transforms

$$\vec{\rho}^{\,2} - \vec{\lambda}^2 \rightarrow \vec{p}_\lambda^{\,2} - \vec{p}_\rho^{\,2}, \vec{\rho} \cdot \vec{\lambda} \rightarrow -\vec{p}_\rho \cdot \vec{p}_\lambda. \tag{44}$$

In the nonrelativistic limit the longitudinal momentum fractions $x_j \rightarrow 1/3$, and

$$3(M_1 + M_2 - 2M_3) \rightarrow \vec{p}_\rho^{\,2} - \vec{p}_\lambda^{\,2}, M_2 - M_1 \rightarrow -2\sqrt{3}\vec{p}_\rho \cdot \vec{p}_\lambda, \sum_j M_j - 9m_q^2 \rightarrow 3(\vec{p}_\rho^{\,2} + \vec{p}_\lambda^{\,2}). \tag{45}$$

The translation of the spin-isospin wave functions to the uds-basis on the light cone is discussed in detail in ref.4. Altogether the $[70, 0^+]$ wave function on the light cone takes the form

$$\psi_N = a_{56}\psi_{56} - a_{70}\psi_{70}$$

$$\psi_{56} = \phi_0 N_0\{J_N(13, 2) + J_N(23, 1)\}$$

$$\psi_{70} = N_\lambda\phi_0(M_1 + M_2 - 2M_3)[J_N(13, 2) + J_N(23, 1)]/\alpha^2 + N_\rho\phi_0(M_2 - M_1)J_N(12, 3)/\alpha^2 \tag{46}$$

with J_N of Eq.(2). The positive constants N_ρ and N_λ normalize each of the mutually orthogonal terms in ψ_{70} of Eq.(46). The structure function $F_2(x)$ can be calculated from the parton model formulas, Eqs.21,22, which are derived along lines similar to Section 4.

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VI. DISCUSSION OF RESULTS AND CONCLUSION

Our numerical results for the electromagnetic form factors (based on pointlike constituent quarks with a mass $m_q \sim m_N/3$, without anomalous magnetic moments and axial vector quark coupling constant $g_A^q = 1$ at $q^2 = 0$) reproduce the static properties of the proton and neutron in ref.4 for $D = 0$, providing a test of our numerical and symbolic codes. The deformation parameter $D = 0.37$ is obtained from the ratio of neutron to proton structure functions $F_2^n(x)/F_2^p(x)$. This deformation corresponds to attraction between scalar $u - d$ quark pairs in the nucleon and is causing relatively minor changes in the electromagnetic form factors of the nucleon which are shown in Figs.1,2. E.g., for $m_q = 0.33$ GeV/c^2, we obtain the nucleon magnetic moments $\mu_p = 2.475$ n.m. and $\mu_n = -1.58$ n.m. which increase in absolute value by 5% to 15% when pion cloud corrections are included.[19]

For $D = 0$, we also obtain the constant $SU(6)$ value 2/3 for $F_2^n(x)/F_2^p(x)$. For $D \neq 0$ the $SU(6)$ symmetry is broken and $F_2^n(x)/F_2^p(x)$ is no longer constant, but falls off with x increasing towards 1, as shown by the solid line in Fig. 3, provided there is attraction between scalar $u - d$ quark pairs ($D = +0.37$). For repulsion, $D = -0.37$, a positive slope is obtained (dot-dashed line in Fig.3). This feature also shows up in the results for the mixed [56]-[70] wave function of Section 5 which incorporates approximately the main effect of the spin force from color magnetism (dotted line in Fig.3). Reversing the phase of the admixture coefficient a_{70} yields a positive slope (dashed line in Fig.3). The sensitivity of this ratio of structure functions for $x > 1/4$ to the spin force is remarkable. Thus, the slope of $F_2^n(x)/F_2^p(x)$ for $x > 1/4$ is a sensitive probe of the spin interaction between quarks.

These structure functions have been calculated at the low energy scale μ in Section 4, where the nucleon is taken to consist of constituent valence quarks only, while sea quarks and gluons are neglected. The results at high q^2 are generated radiatively by means of a perturbative QCD evolution which depends on the running coupling constant α_s that contains the renormalization group scale parameter Λ_{QCD} in logarithmic form $\ln(-q^2/\Lambda_{QCD}^2)$. The results from the evolution do not depend on the scale μ or Λ_{QCD} separately, but on the

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logarithmic ratio $L = \ln(-q^2/\Lambda_{QCD}^2)/\ln(\mu^2/\Lambda_{QCD}^2)$. Based on the value $\Lambda_{QCD} \sim 0.2$ GeV, $L = 14.7$ has been extracted[18] from the second moment $< F_2^N(-q^2 = 15 \, \text{GeV}^2) >_2 = 0.127$ of the (average) nucleon structure function from the EMC data for the deuteron. This value of L yields the low energy scale $\mu \sim 0.25$ GeV,[18]a value that is consistent with $\alpha \sim m_q \sim m_N/3$, but so low that a perturbative evolution gives rise to large changes of quark distributions and structure functions and is not trustworthy. Nonetheless it is interesting to note that our results for $F_2^p(x)$ in Fig.4 and $xu_v(x)$ in Fig.5 and those in ref.18 are similar. Our results for the valence quark probability $u_v(x)$ are shown (as solid line for the attractive spin force, $D = 0.37$, and dashed line for the mixed [56]-[70] color hyperfine wave function) in Fig.5 and are to be compared with the dot-dashed curve from (Fig.3 in) ref.18 corresponding to the Isgur-Karl quark model. The smaller dot-dashed curve is their result of an evolution from $(0.25 \, \text{GeV})^2$ to $15 \, \text{GeV}^2$. (Note that the perturbative evolution is known to become unreliable near the endpoints $x = 0$ and 1.) While these evolution effects are large for $xu_v(x)$, they are much smaller, though not negligible, for the ratio $F_2^n(x)/F_2^p(x)$ for $x > 1/4$. Hence light-cone quark model results for **ratios** of structure functions are more reliable because of their much smaller modifications due to the QCD evolution. In order to avoid the evolution at too low q^2, we have extracted the structure functions $F_i(x, q^2)$ from the hadronic tensor and evolved them from $-q^2 = (0.6 \, \text{GeV})^2$, where our relativistic quark model is still valid, but $F_2(x, q^2) \neq 2xF_1(x, q^2)$. At $-q^2 = 15 \, \text{GeV}^2$ we have verified that $F_2(x, q^2) = 2xF_1(x, q^2) \sim F_2(x)$. These results are shown in the dot-dashed and short-dashed lines in Fig.4. From the latter we now see more clearly the missing sea-quarks at $x < 1/3$. Note that the shift of the F_2^p peak to smaller x mainly comes from the QCD evolution. Choosing a higher value than $(0.6 \, \text{GeV})^2$ makes the QCD corrections too small. However, including sea quarks that mainly contribute at small x would effectively shift the $F_2^p(x)$ peak to lower x values, allow us to raise the lower limit $(0.6 \, \text{GeV})^2$ of perturbative QCD corrections and extend the validity of the model to lower x.

The different slope results in Fig.6 (see also ref.24 for a discussion of earlier work) show

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that $F_2^n(x)/F_2^p(x)$ is also sensitive to the boosts built into the Melosh transformations, which are missing in the nonrelativistic Karl-Isgur wave function used in ref.18. (Note also that in the relativized NQM versions of ref.15 the relevant $[70, 0^+]$ admixture coefficient a_{70} does not change by much.)

Our result for the polarization asymmetry $A_1^p \simeq 2xg_1^p(x)/ F_2^p(x)$ (the solid line in Fig.7) is also in fair agreement with the EMC data in the valence quark region. (A perturbative QCD evolution of the solid line is shown in Fig.7 as dot-dashed line which we consider as unreliable. The data are nearly q^2 independent.)

In summary, the polarization asymmetry of the proton and the ratio of neutron to proton structure functions are sensitive probes of the spin force between quarks. Such ratios of structure functions are observables that are only moderately affected by uncertainties involved in a perturbative evolution to high momentum. Electromagnetic nucleon form factors and ratios of deep inelastic structure functions are compatible in a constituent light-cone quark model with an attractive spin force.

FIGURES

FIG. 1.   Magnetic proton form factor normalized to the dipole shape $(1 - q^2/m_D^2)^2$ for $m_D^2 = 0.71$ GeV^2. The solid line is our light-cone quark model with $\alpha = 0.35$ GeV, $m_q = 0.33$ GeV, $D = 0.37$ with attractive spin force, the dashed line is for $D = 0$,[4] no spin force. The dot-dashed line represents the nonrelativistic constituent quark model (NQM). The experimental data are from ref.20.

FIG. 2.   Proton charge form factor normalized to the dipole shape. The curves are denoted as in Fig.1

FIG. 3.   Ratio of unpolarized neutron to proton structure functions. The solid line is for attraction in scalar $u - d$ quark pairs in the light-cone quark model with $D = 0.37$. The dot-dashed line is for repulsion, $D = -0.37$. The dotted line is for the spin force from color magnetism and the dashed line is with opposite sign of $a_{70}(= -0.2)$. Data are from ref.21.

FIG. 4.   Unpolarized proton structure function $F_2^p(x)$. The upper solid line is for the attractive spin force, $D = 0.37$, in the light-cone quark model; the lower solid line is its evolution from $(0.25$ GeV$)^2$ to 15 GeV^2 based on ref.22. The upper dashed line is for the spin force from color magnetism. The dot-dashed line is $F_2^p(x, q^2)$ at $-q^2 = (0.6$ GeV$)^2$ from the hadronic tensor at the $\mu = 0.25$ GeV scale of the light-cone quark model; the short-dashed line is its evolution from $(0.6$ GeV$)^2$ to 15 GeV^2. Data are from ref.23.

FIG. 5.   Up quark distribution $xu_v(x)$. The solid line is for attraction in $u - d$ quark pairs, $D = 0.37$. The dashed line corresponds to the spin force from color magnetism. The large dot-dashed line corresponds to the Isgur-Karl quark model result from ref.18 and the smaller one is their result evolved from $(0.25$ GeV$)^2$ to 15 GeV^2. The EMC data are from ref.7.

FIG. 6.   Ratio of unpolarized neutron to proton structure functions for the Isgur-Karl model from ref.18 (dotted line) and evolved from $(0.25$ GeV$)^2$ to 15 GeV^2 (dot-dashed line). The solid line is for attraction with $D = 0.37$. The EMC data are from ref.21.

FIG. 7. Proton asymmetry $A_1^p(x)$ with data from refs.7 and 25. The solid line is for attraction between $u-d$ quark pairs, $D=0.37$, in the light-cone quark model and the dot-dashed line its evolution from $(0.6 \text{ GeV})^2$ to 11 GeV^2; the dashed line is for the spin force from color magnetism.

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